Teaching the Dynamic Earth

Plate Tectonics Interactive

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Plate Tectonics Interactive

an interaction between presenter and audience on Earth's structure and plate tectonics

Objectives: To present plate tectonics and the structure of the Earth, not as fact, but as scientific theory that requires evidence and explanation – and to use this as a model of how scientific theories in general can be developed.

The National Science Curriculum (2000) Perspective

The session is aimed at the following National Science Curriculum statements:

Key Stage 4, Sc4 Waves – Seismic Waves

"Pupils should be taught:

- **m) that longitudinal and transverse earthquake waves are transmitted through the Earth, and how their travel times and paths provide evidence for the Earth's layered structure;**
- **n) that the Earth's outermost layer, the lithosphere, is composed of plates in relative motion, and that plate tectonic processes result in the formation, deformation and recycling of rocks."**

Key Stage 4, Sc1 - Scientific enquiry

"Pupils should be taught:

- **1a) how scientific ideas are presented, evaluated and disseminated [for example, by publication, review of other scientists]**
- **1b) how scientific controversies can arise from different ways of interpreting empirical evidence.**
- **1c) ways in which scientific work may be affected by the contexts in which it takes place, and how these contexts may affect whether or not these ideas are accepted.**
- **1d) to consider the power and limitations of science in addressing industrial, social and environmental questions, including the kinds of questions science can and cannot answer, uncertainties in scientific knowledge, and the ethical issues involved."**

Activities and Demonstrations

1 Model Earth – a simulation of density contrasts within the Earth

Groups of students are given a pair of Plasticine spheres, of equal size. One is made of solid Plasticine: the other has a ball bearing inside, occupying roughly half the diameter. Students are asked to compare the spheres and say how they might work out what is inside. When they have worked out a range of ideas, these are applied to the Earth, to consider if they could be used to provide evidence on the Earth's structure. The relative density of the Earth is around 5.5, but the average relative density of surface rocks is only about 2.8, so the interior must be considerably denser. A typical igneous rock of the continents is granite, with a relative density of about 2.7. This activity is described in more detail in: King, C. (2002) The secrets of Plasticine balls and the structure of the Earth: investigation through discussion. *Physics Education*, **37(6)**, 485 – 491.

2 Earthquakes – the slinky simulation

A well known demonstration. Giving the slinky a sharp push-pull motion produces a longitudinal wave (known as a **P** wave – **P**ush/**P**ull: **P**rimary wave, because it travels faster than other types of wave). Giving the slinky a sharp sideways shake produces a transverse wave (known as an **S** wave - **S**ideways, **S**hake, **S**hear, **S**low wave). Both these types of wave travel through the Earth and are known as body waves. Surface waves, which cause most of the damage in an earthquake, are more akin to sea waves and are more difficult to imitate with the slinky.

3 Wave motion – student 'molecules'

Students line up with straight arms, holding the shoulders of the person in front. The rear student (the most trustworthy!) applies a gentle push/pull motion, which ripples through the line, imitating a P wave being transmitted by a solid. Shaking the students from side to side imitates an S wave in a solid. Students drop their arms. The trusted student waggles the one in front of him/her from side to side, but no motion passes down the line: an analogy for an S wave *not* being transmitted through a liquid. Students then close up together with arms down. A gentle push at the rear causes a 'P wave' to travel through a 'liquid', although the analogy breaks down when the front student falls over and the pulse is not sent back again!

4 The china plate analogy

Use a chipped china plate to draw an analogy with the plates of the Earth's lithosphere: thin; curved; rigid; brittle; all the damage is at the edges.

5 Partial melting demonstration

Prepare two beakers, (250ml or smaller). Pour some gravel and some melted wax into each beaker. As the mixture sets, stir it, so that the wax and gravel are mixed as uniformly as possible. Then gently heat one beaker again, so that the wax melts and rises above the gravel, and allow it to set. The beaker with the uniform mixture represents the rocks of the Earth's upper mantle, with a range of minerals of different melting points.

Raising the temperature causes the minerals with lower melting points to melt first, and to rise, producing igneous rocks with a different composition from the original material, imitated in the second beaker. This happens at oceanic ridges where iron and magnesium-rich (silicon-poor) mantle rocks produce basaltic magmas, with proportionately lower ratios of iron and magnesium (and more silicon). If the magma reaches the surface, it produces **basalt** lava. If it sets just below ground, it produces **dolerite**: cooling at greater depths results in coarse-grained **gabbro**. Further partial melting of basaltic rocks at destructive margins produces rocks which are even more deficient in iron and magnesium (and richer in silicon), called **andesites**. The partial melting of the wax versus gravel may be done in front of the class, or prepared in advance as a demonstration.

6. Properties of the mantle – the potty putty demonstration

Students (and many text book authors!) find it difficult to visualise how a solid mantle can 'flow', allowing convection currents to occur. The potty putty demonstrates three physical properties: a) elastic behaviour, when it is bounced; b) plastic deformation when it is allowed to droop; and c) brittle failure when hit with a hammer, or pulled sharply.

a) equates to the mantle allowing seismic waves (both P and S) to pass through;
b) equates to the mantle being able to 'flow' over time, and allow convection to happen;
c) equates to brittle failure in the mantle, producing earthquakes. Seismic evidence suggests that the mantle can show brittle failure to a depth of up to 700 km.

7 Plates in motion – the cardboard replica

The making of the models can be set as a homework, given Fig. 23 for guidance. Pulling on the thin card tag below the model causes 'subduction' of the card (the dense 'oceanic lithosphere'), whilst the low density 'sediments' pile up between the wooden 'continents' to form a 'mountain range' and will not disappear down the 'subduction zone' (unless the slot has been made too wide!).

8 'Frozen' magnetism in rocks – iron filings in wax or glue: magnetisation of real rocks

Students are familiar with the shaking of iron filings onto a card over a bar magnet. If the card is first spread with spray glue, the iron filings remain in the position of the magnetic field, even when the magnet is removed. This is analogous to a rock holding a previous magnetisation, even after the Earth's field has changed. Alternatively, the filings can be shaken into a petri dish of molten wax over the bar magnet and the wax allowed to set.
Some igneous rocks are so strongly magnetised that a good magnetic compass will be deflected by several degrees, and North and South pole positions can also be located. Ask for an off-cut of 'black granite' (gabbro) from a monumental mason, or demolition merchant.

9 The magnetic ocean floor and sea floor spreading – a simulation.

Prepare a strip of thin card or paper (e.g. 50 x 20cm) as shown in Fig. 11. Colour in alternate stripes, **symmetrically** about the midline. Stick dressmakers' pins in each section, pointing **alternately**, as shown in the diagram.

Fold the sheet and slot it down between two benches, so that most of it is hidden. Explain that this represents an oceanic ridge, like the Mid-Atlantic Ridge, with magma welling up, cooling and crystallising. Once it has dropped below a certain temperature, it is capable of acquiring an induced magnetisation from the ambient magnetic field of the Earth.

Draw up the sheet as shown. As the first set of pins appears, magnetise them by gently stroking them repeatedly with the North end of a strong bar magnet, stroking towards the point. As the next set of pins appears, stroke them with the North end of the magnet, again towards the point. Continue *ad nauseam*.

Put the magnet well out of reach, and then test the polarity of each set of pins with a good magnetic compass. This should reveal that the pins (the 'basaltic rocks of the ocean floor') in the shaded sections are magnetised in the opposite direction to those in the un-shaded sections. This is analogous to the reversed polarity of magnetisation, acquired when the Earth's magnetic field periodically reverses. (The compass is being used like a magnetometer being towed by a ship across the surface of the ocean, detecting magnetic changes in the rocks of the ocean floor below).

10 Plates on a curved surface – paper on a globe demonstration

Place two sheets of A4 paper, touching, on the surface of the globe. Pull them away from each other, to show that the rate of separation is different along the length, because of the curvature of the globe. When two plates pull apart in reality, faulting occurs at intervals across the junction, the faults being termed transform faults.

11 Continental jigsaws – reconstructing parts of Pangaea

Ensure that you photocopy the various jigsaw maps onto thin card before you cut them up! Prepare enough for the class to work in small groups, and try to use a different coloured card for each of the sets of maps on any one theme, to help avoid the bits becoming muddled up when they are collected in.

Apparatus and materials

Slide projector, digital projector or overhead projector, plus slides in the appropriate format
Adequate blackout for lab

1 A pair of Plasticine spheres per group - one with a large steel ball bearing inside. (Balance, density can, or callipers, if quantitative work is planned). A sample of granite.
2 'Slinky' spring
3 4 or 5 willing students!
4 A china plate, preferably chipped at the edges
5 2 prepared beakers, containing coloured wax and gravel. Demonstration samples of basalt, dolerite, gabbro and andesite, if available.
6 'Potty putty'. This may be bought from 'good' toyshops. The recipe was given in *Chemistry Review* **9.1**, September 1999, published by Philip Allan Updates on behalf of the University of York.
7 'Plates in motion' model, made from cardboard, with paper serviettes, two small wooden blocks and paper clips (See Fig. 23).
8 Bar magnet, iron filings, either set in wax in a petri dish, or in glue on paper. Sample of naturally magnetised, dark, igneous rock (e.g. gabbro)
9 Bar magnet, orienteering compass, pins, strip of paper with stripes, access to a crack between two benches, or piles of books etc. (see Fig. 11)
10 Globe, two sheets of paper
11 'Jigsaws' prepared by photocopying the master sheets on card and cutting round outlines. One set of each 'jigsaw' is required for each small group of students.

Acknowledgements and further reading

The student activities are mostly taken from: 'Investigating the Science of the Earth, SoE2: Geological changes – Earth's Structure and Plate Tectonics', ESTA. Available from ESTA, earthscience@macunlimited.net (£2.50 + p&p).

ESTA's 'Earth's Surface Features' contains further work related to plate tectonics and to the deformation of rocks often associated with it. Available from ESTA, earthscience@macunlimited.net (£2.00 +p&p).

The use of students to model wave motion is derived from Whitehead, P. (1992) *Co-ordinated Science: The Earth*, OUP, Oxford: p. 59.

The implications of the Plasticine sphere simulation are discussed in King, C. (2002) The secrets of Plasticine balls and the structure of the Earth: investigation through discussion. *Physics Education*, **37 (6)**, 485 – 491

The master sheets for 'continental drift' are traced from various sources, most notably the Open University (1996) *S102: Plate tectonics: a revolution in the Earth sciences*.

Photographic slides used during the presentation are taken from:
Slides taken by Peter Kennett
'Plate Tectonics', a film strip by Visual Publications (now out of print?)

Diagrams in books:
Press, F. & Siever, R. (1994) *Understanding Earth* W. H. Freeman & Company, New York.
Kious, W.J. & Tilling, R.I. (1996) *This Dynamic Earth: the Story of Plate Tectonics*, USGS Special Publication (on sale via ESTA, £7), also available on the USGS website: http://pubs.usgs.gov/publications/text/dynamic.html

Waves in the Earth

Fig: 1 Seismic velocities plotted against depth below the Earth's surface
Source: SoE2: Geological changes – Earth's structure and plate tectonics, ESTA, 1996

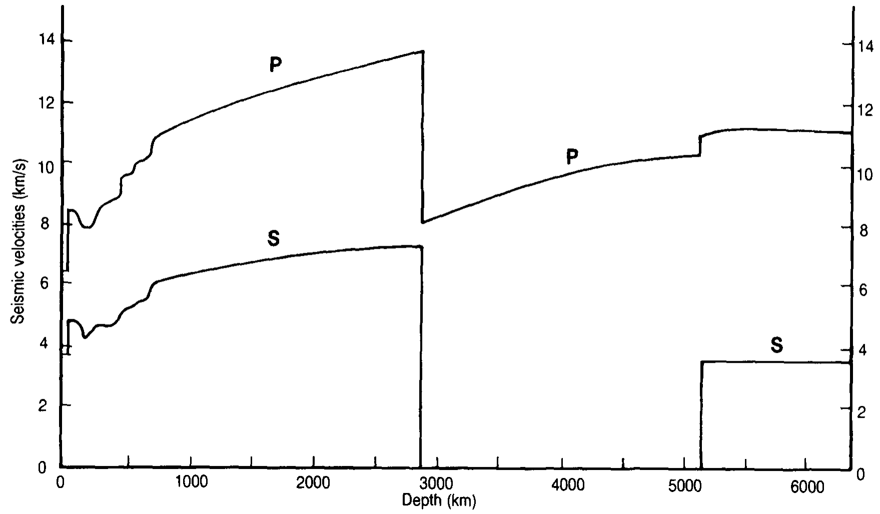


Fig 2: Summary of the layered structure of the Earth
Source: SoE2, ESTA, op. cit.

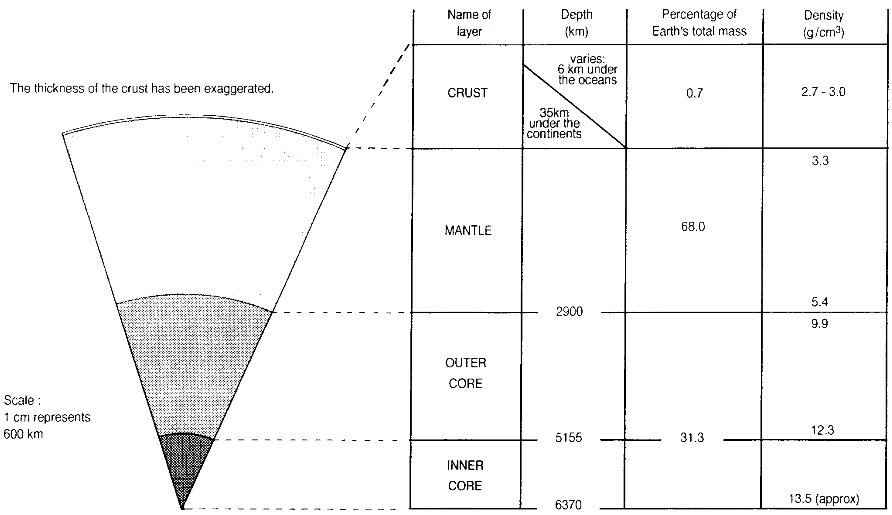


Fig 3: The outermost layers of the Earth

Depth in km	**Compositional (chemical) layering**	**Mechanical (physical) layering**
0 – **mean of 15**	Crust	Lithosphere
about 100	Mantle	Lithosphere
about 250	Mantle	Asthenosphere
	Mantle	The rest of the mantle

NB. The crust has a mean thickness of 35km beneath continents and 6 km beneath oceans giving an overall mean of about 15 km.

Fig 4: The shadow zone from an earthquake in Japan
Source: Aspects of Geology, Kennett and Ross, Longmans, 1984 (out of print).

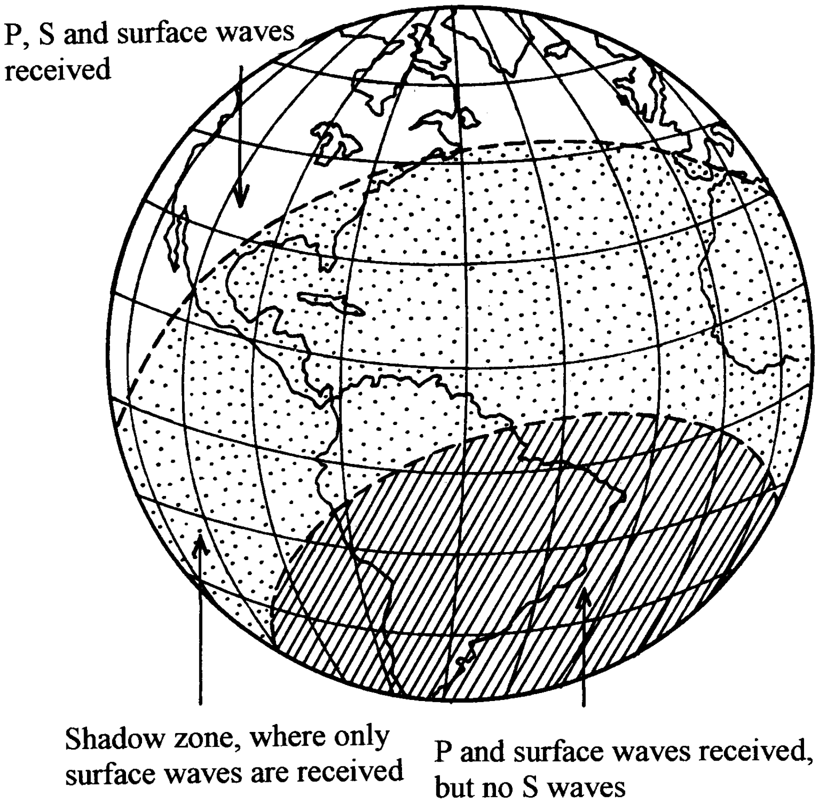
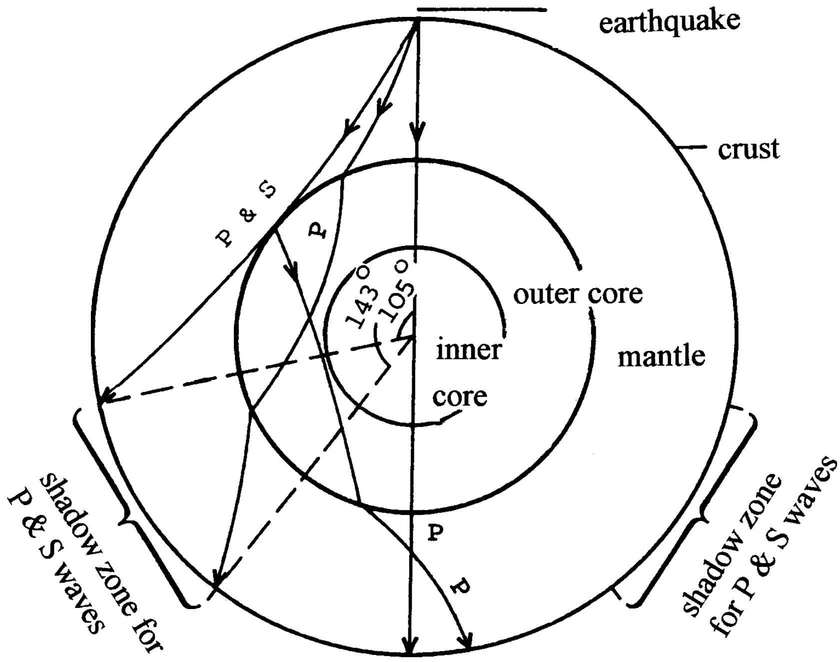


Fig 5: The paths of selected P and S waves through the Earth
Source: Aspects of Geology, op. cit.



The Interior of the Earth

Fig 6: The internal structure of the Earth
larger diagram NOT drawn to scale; smaller diagram drawn to scale
Source: This Dynamic Earth, Kious & Tilling, USGS, 1999

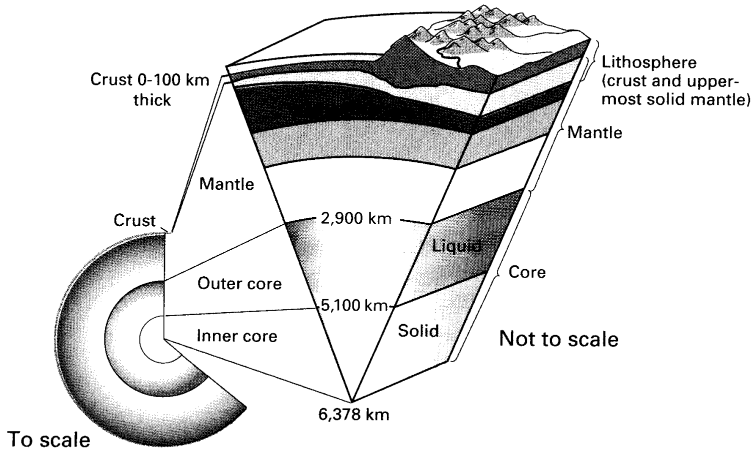


Fig 7: The pattern of heat flow out of the ocean floor.
High values occur over the oceanic ridges and low values over the deep trenches. Values rise again over volcanic island arcs.
Source: Geoscience: Understanding Geological Processes, eds Edwards & King, Hodder & Stoughton, 1999

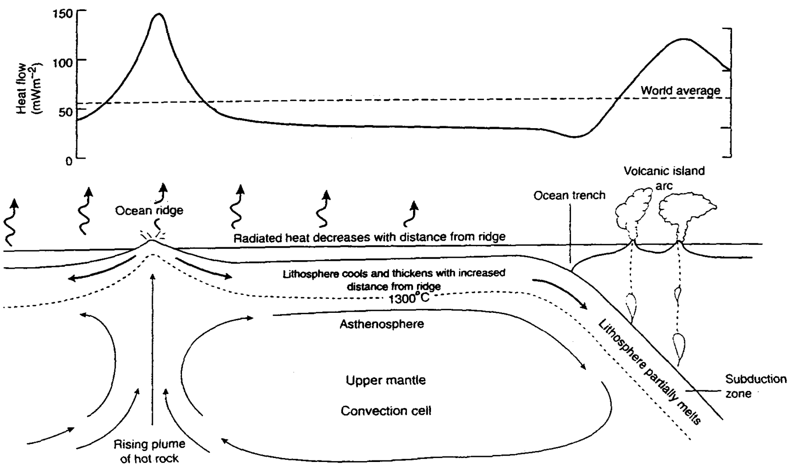
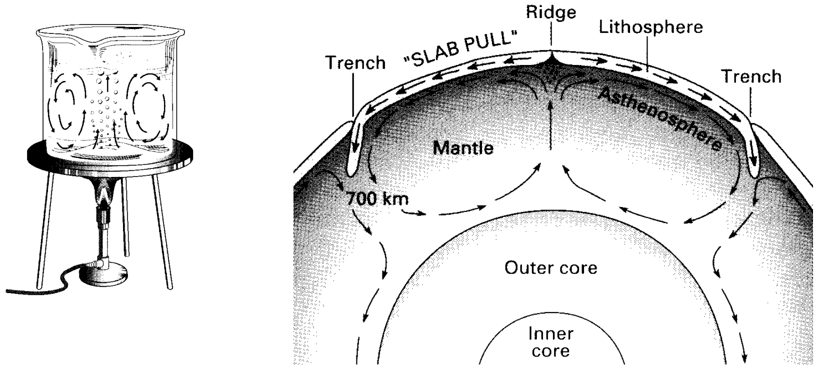


Fig 8: Convection
Source: This Dynamic Earth, op. cit.

a) A well-known laboratory model, using a dye in water.

b) One of several proposals for deep-seated, slow moving convection cells in the mantle.



The Magnetic Evidence

Fig 9: Symmetrical magnetic 'stripes' on the ocean floor.
The solid line shows a magnetic profile measured above the East Pacific Rise. It is matched to a profile calculated for alternatively normally and reversally magnetised rocks of the ocean floor (dotted line). The model uses known reversals and dates from similar rocks on land, e.g. in Iceland.
Source: This Dynamic Earth, op. cit.

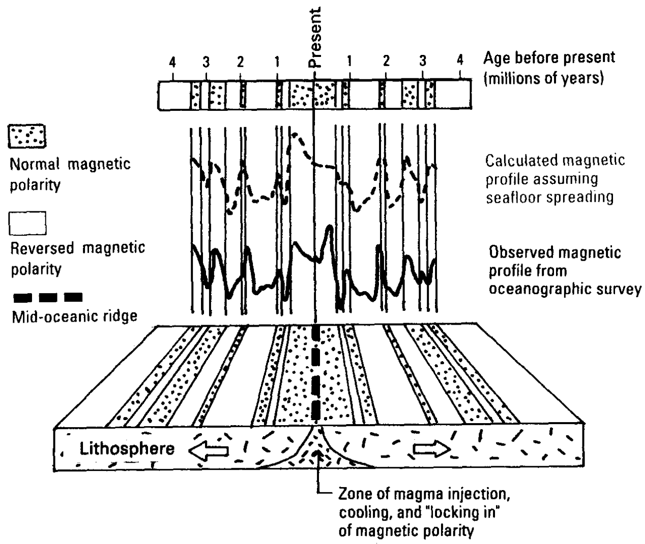


Fig 10: Measured magnetic anomalies
over the Reykjanes Ridge, near Iceland, showing 'magnetic stripes' (positive anomalies black) and their bilateral symmetry.

Source: Aspects of Geology, op. cit.

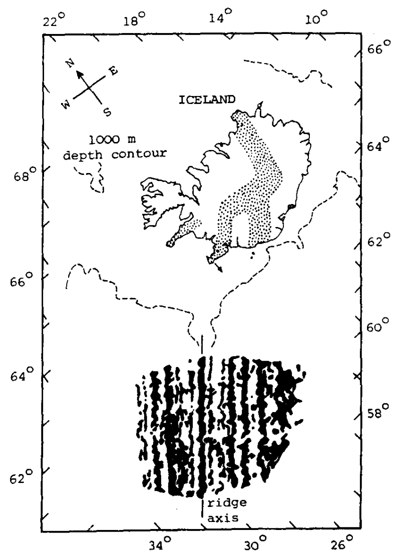
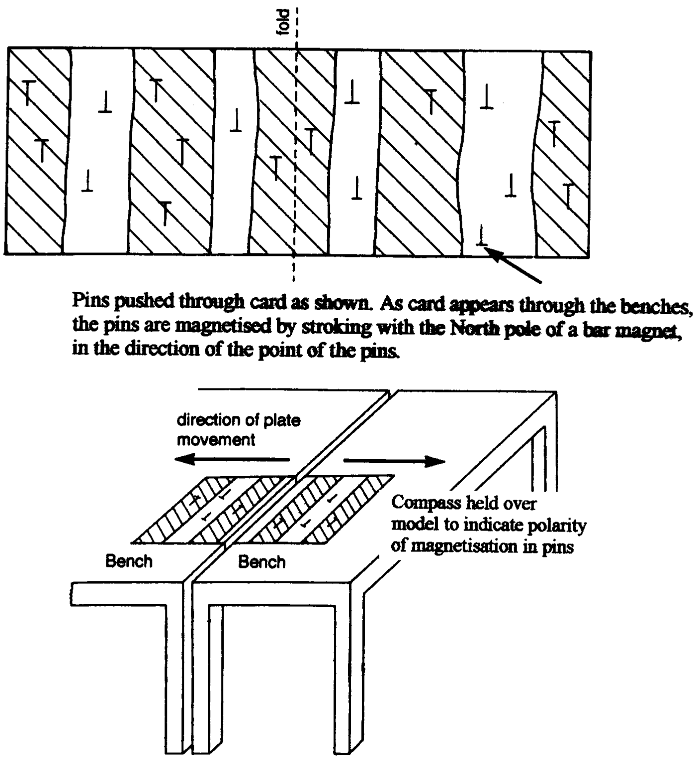


Fig 11: A simulated ocean floor, made with a shaded piece of card and sewing pins, and the 'ocean floor' appearing between two benches
Source: SoE2, ESTA, op. cit.



Constructive Plate Boundaries

Fig 12: Detail of a constructive plate boundary
Source: SoE3: Geological Changes - Rock Formation and Deformation, ESTA, 1998, after 'Story of the Earth', HMSO, 1972

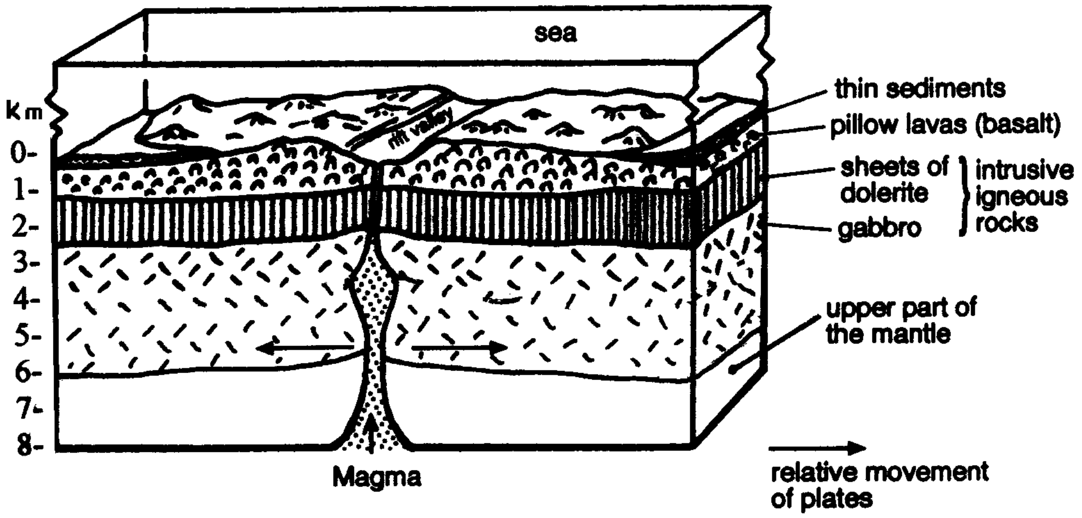


Fig 13: A simplified version of a constructive plate boundary
Source: SoE2, ESTA, op. cit.

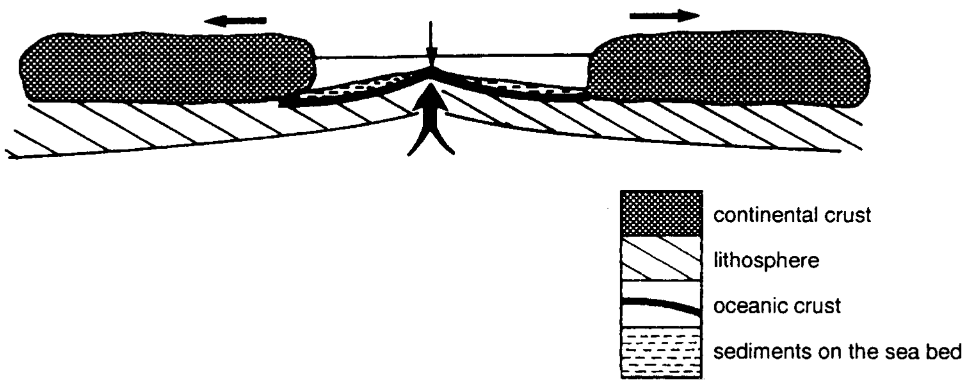
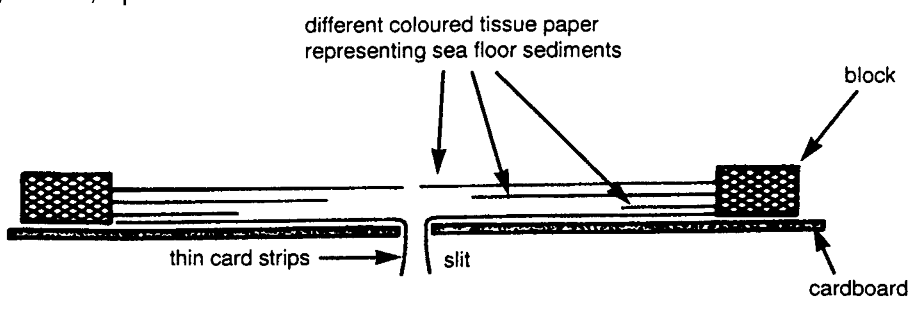
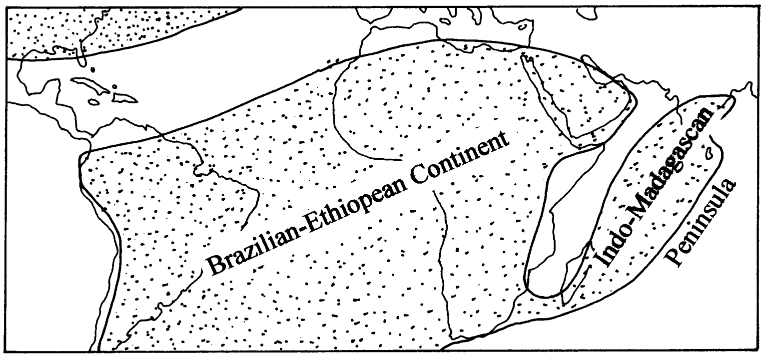


Fig 14: Model of a constructive plate boundary
Source: SoE2, ESTA, op. cit.

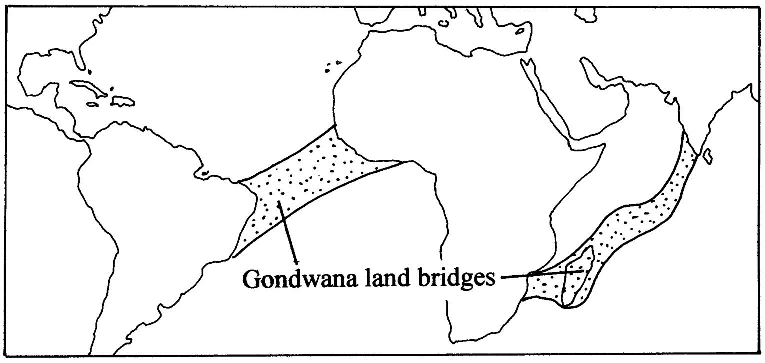


An older theory, and current evidence from earthquakes

Fig 15: Land bridge theory
Source: Continental drift and the fossil record, A Hallam, Scientific American offprint 903. Freeman, 1972

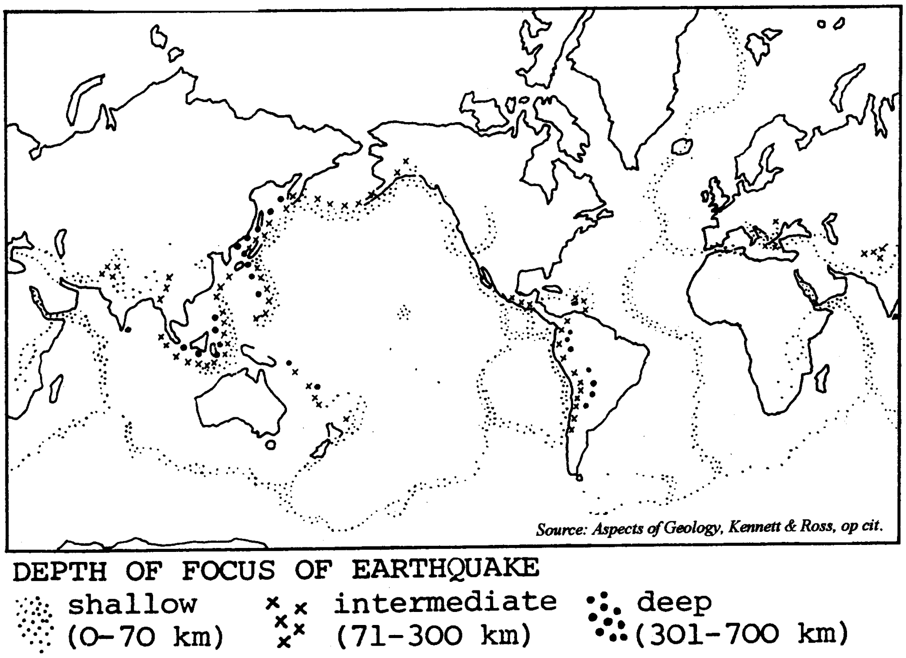


The "Forth Bridge" model!, 1887



The "Millennium Bridge" model!, mid 20th Century

Fig 16: Distribution of earthquakes
Source: SoE3: Geological Changes - Rock Formation and Deformation, ESTA, 1998, after 'Story of the Earth', HMSO, 1972



Destructive plate boundaries

Fig 17: The distribution of earthquake foci beneath an oceanic trench.
Such a sloping zone is known as a Benioff zone, also known as a subduction zone, or destructive plate margin.
Source: Geological Science, McLeish, Nelson, 1992

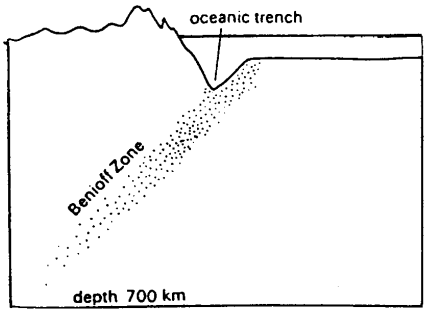


Fig 18: Convergence of 2 two oceanic plates
Source for Figs 18-21: This Dynamic Earth, op. cit.

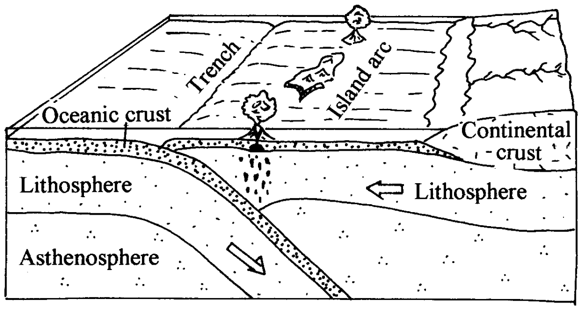


Fig 19: Convergence of an oceanic plate with a continental one

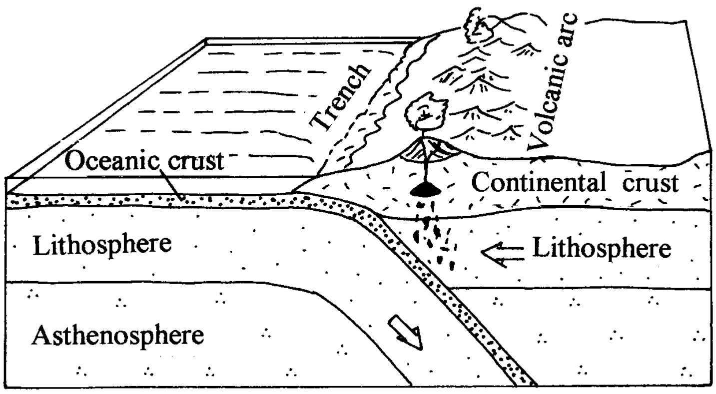


Fig 20: Convergence of two continental plates

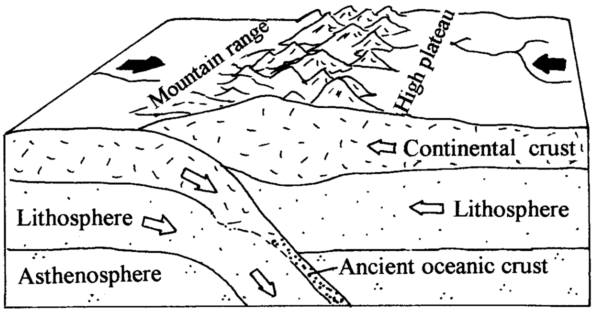


Fig 21: The origin of the Himalayas and Tibetan Plateau

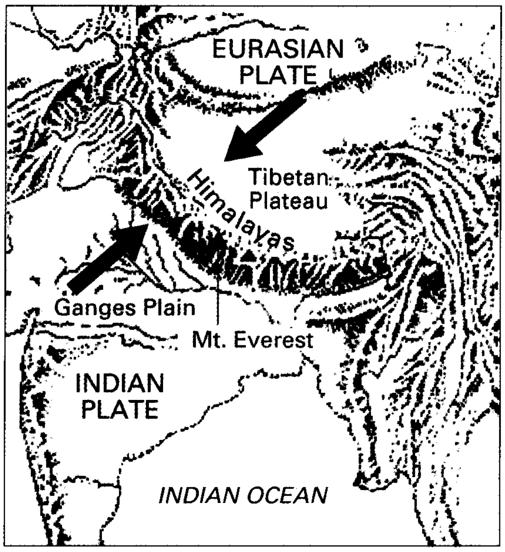


Fig 22: Detail of a destructive plate boundary
Source: SoE2, ESTA, op. cit. After 'Understanding the Earth', Press & Siever, Freeman, 1994

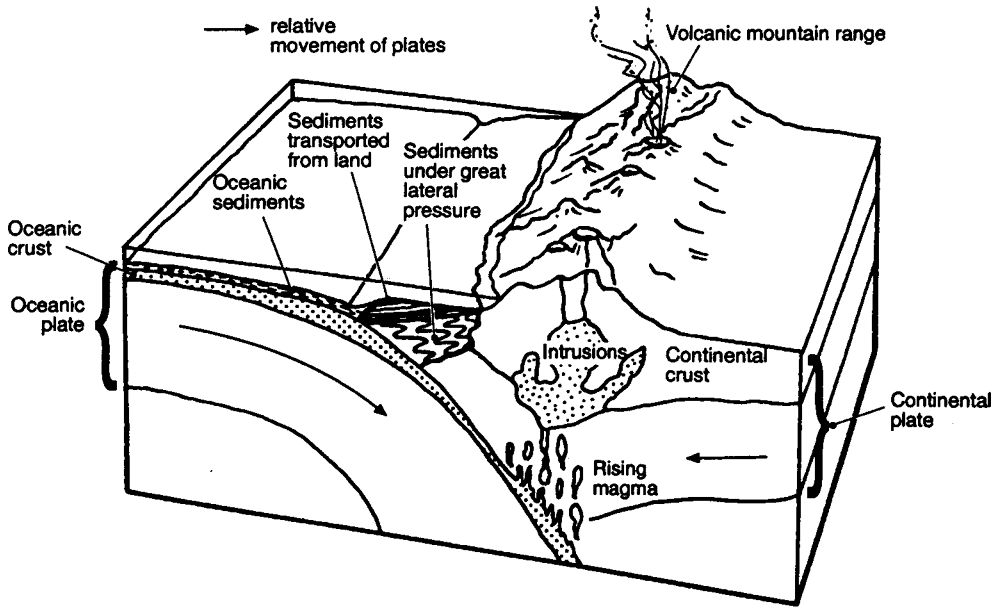


Fig 23: A model of a destructive plate boundary
Source: SoE2, ESTA, op. cit.

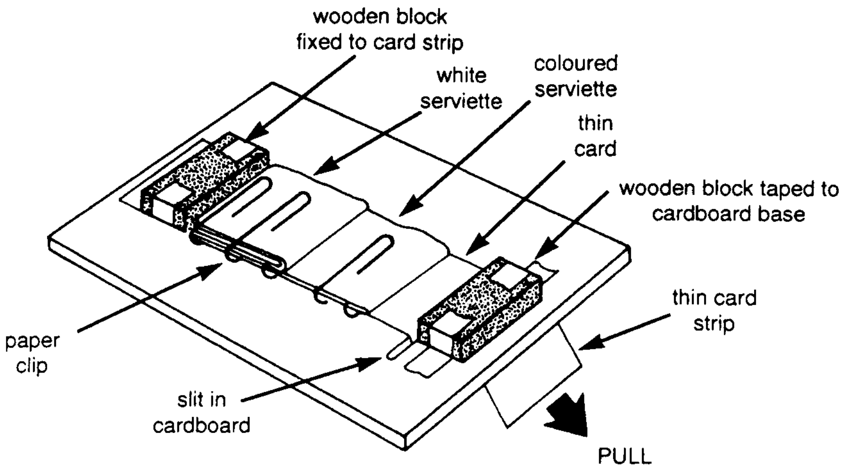


Fig 24: A simplified version of a destructive plate boundary
Source: SoE2, ESTA, op. cit.

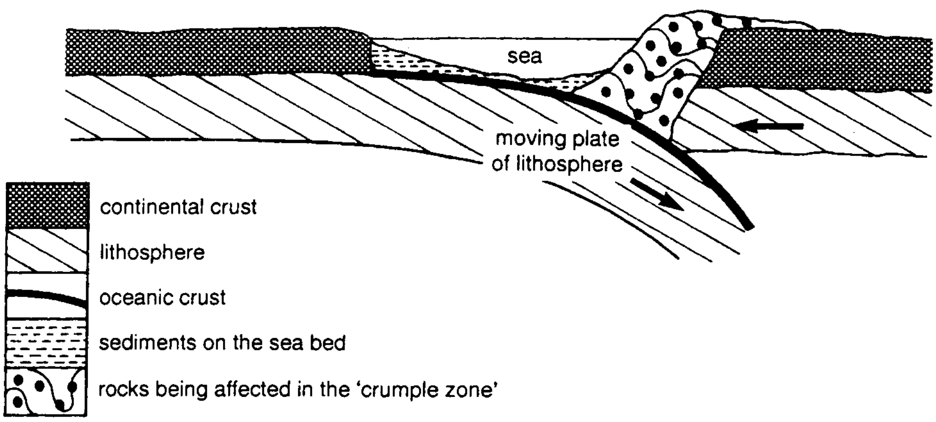


Plate Tectonics - what is the evidence, what are the explanations? (Some answers)

Concept	Description	What is the evidence?	What is the explanation?	Activity numbers refer to activities list
The structure of the Earth	The Earth has crust mantle and core	Seismic evidence Earth's density	Differentiation during cooling and P/T processes	**1** plasticine balls **2** slinky **3** student molecules
Break up of Pangaea	Super continent breaks up and fragments diverge	Matching fossils Matching geological structures Matching of continental shelves Measurements of plate movement	Explanation of each piece of evidence	Computer animation **11** jigsaw exercises
Tectonic plates	The outer part of the Earth is divided into discrete pieces called plates	Active plate margins (earthquakes and volcanoes)	Plate movement causes activity along the margins	**4** china plate demo
Lithosphere thickness	Plates are thin pieces of lithosphere (average 100km thick). Some plates carry continents (lithosphere then up to 300km thick)	Seismic boundary evidence Seismic velocity evidence	Mode of formation of lithosphere	
Lithosphere composition	Oceanic lithosphere composed of iron-rich basaltic materials Continental lithosphere composed of silica-rich granitic materials	Oceanic lithosphere - evidence from obduction (e.g. Cyprus) Continental lithosphere – evidence from exposures, drilling	Mode of formation of lithosphere	
Asthenosphere	Beneath the lithosphere is a layer that can flow	Seismic evidence for the asthenosphere (90-99% solid)	Ductile flow of solid material	**6** silly putty
Plate movement	Over geological time, the lithosphere is moved	Heat flow Magnetic stripes Age of the ocean floor	The solid lithosphere can move over the ductile asthenosphere	**8** frozen magnetism, magnetic gabbro **9** magnetic stripes
Constructive plate boundaries	New plate material is created as plates diverge	Evidence from obduction (basalt, dolerite, gabbro, peridotite) Deep ocean pillow lavas Seismic evidence of magma chambers Magnetic stripes	Basalt, dolerite, gabbro and peridotite formation	**5** partial melting Specimens in vertical order: basalt, dolerite, gabbro, peridotite
Transform faults	Constructive margins are offset	Topographic evidence Earthquake evidence	Divergence on a sphere	**10** globe & paper
Plate collision	When two plates are moved towards one another, one subducts	Heat flow		
Oceanic plate collisions	When two oceanic plates collide, one subducts and partially melts producing volcanoes	Benioff zone Volcano distribution and composition	The more dense plate goes down Partial melting of oceanic lithosphere and overlying sediments	Andesite specimen
Oceanic v continental plate collisions	Subducting oceanic plate produces volcanoes, batholiths and mountain chains	Benioff zone Marginal mountain chains of folded rocks. Volcano composition Batholith composition	Material is scraped up as the plate subducts. The subducting lithosphere and overlying continental material partially melts	Granite specimen
Continental plate collisions	Two continents collide, producing mountain chain	Location of mountain chains within continents; character of mountain chains (nappes etc)	Squeezing of 'sloppy sediments'	**7** cardboard collision model
Hot spots	There are examples of volcanicity far from plate boundaries	Volcanoes in alignment, younger at one end	Rising plumes of mantle material under moving plate	

Plate Tectonics - what is the evidence, what are the explanations? (Some answers)

Concept	Description	What is the evidence?	What is the explanation?	Activity
The structure of the Earth	The Earth has crust mantle and core			• Plasticine balls • Slinky • Student molecules
Break up of Pangaea	Super continent breaks up and fragments diverge			• Computer animation • Jigsaw exercises
Tectonic plates	The outer part of the Earth is divided into discrete pieces called plates			• China plate demo
Lithosphere thickness	Plates are thin pieces of lithosphere (average 100km thick). Some plates carry continents (lithosphere then up to 300km thick)			
Lithosphere composition	Oceanic lithosphere composed of iron-rich basaltic materials Continental lithosphere composed of silica-rich granitic materials			
Asthenosphere	Beneath the lithosphere is a layer that can flow			• Silly putty
Plate movement	Over geological time, the lithosphere is moved			• Frozen magnetism • Magnetic gabbro • Magnetic stripes
Constructive plate boundaries	New plate material is created as plates diverge			• Partial melting • Specimens in vertical order: basalt, dolerite, gabbro, peridotite
Transform faults	Constructive margins are offset			• Globe & paper
Plate collision	When two plates are moved towards one another, one subducts			
Oceanic plate collisions	When two oceanic plates collide, one subducts and partially melts producing volcanoes			• Andesite specimen
Oceanic v continental plate collisions	Subducting oceanic plate produces volcanoes, batholiths and mountain chains			• Granite specimen
Continental plate collisions	Two continents collide, producing mountain chain			• Cardboard collision model
Hot spots	There are examples of volcanicity far from plate boundaries			

Teaching Points of ESEU Workshop Activities: Plate Tectonics Interactive

Activity	Pattern (construction)	Challenge (cognitive conflict)	Explanation of thinking (metacognition)	Relevance (bridging)	Practical teaching points
1. Plasticine balls	Formulating ideas to explain the mass/density difference	Developing ideas to 'probe' the ball to discover the reason for the differences in mass/density	Discussion with probing by teacher	Relating Plasticine ball ideas to real Earth ideas: • probing with needle ≡ coring (≡ mosquito bite on an elephant) • ultrasound ≡ seismic (shock) waves • X-ray – not possible on Earth • using a magnet – like using a compass to detect Earth's field	Use different colours of Plasticine for different balls to make it easier to sort them later.
2. Slinky spring		Why can't S (shear) waves be transmitted through liquids?			White spots (Tippex) on slinky show movement directions of individual particles. S-waves not transmitted through liquids because when the particles move sideways (shear) they don't bounce back.
4. China plate v tectonic plate		What are the similarities?	Discussion		Both are broad but thin, rigid, brittle and curved.
6. Potty/silly putty		What affects how a solid responds to stress?	Discussion	What other solids behave like this (ice – tap with a hammer = rebound (elastic) hit harder – fracture, flows under pressure (glacier))	The two controlling factors are amount of stress and amount of time. Temperature would also have an effect
9. Magnetic stripes with magnetised pins		Why don't the 'real' magnetic stripes south of Iceland look like the black and white stripes of the model?	Discussion		Stripes are formed by magnetism of lava flows
10. Paper/globe demo					The orange segment-shaped space created by movement shows the need for transforms.
11. Jigsaw cutouts	Reconstruction of the Pangaea map (based on movement from map of the world today)	How to use the information given on the various cutouts	Discussion in groups	Where else do we find slabs of solid material moving about like this? (e.g. solid lava on a lava lake, ice flows	If you photocopy different jigsaw versions on to different colours of paper – they are much easier to sort afterwards. Cut out acetate versions can be used on an OHP.